Open heavy-flavour results from ALICE

Francesco Prino

INFN – Sezione di Torino

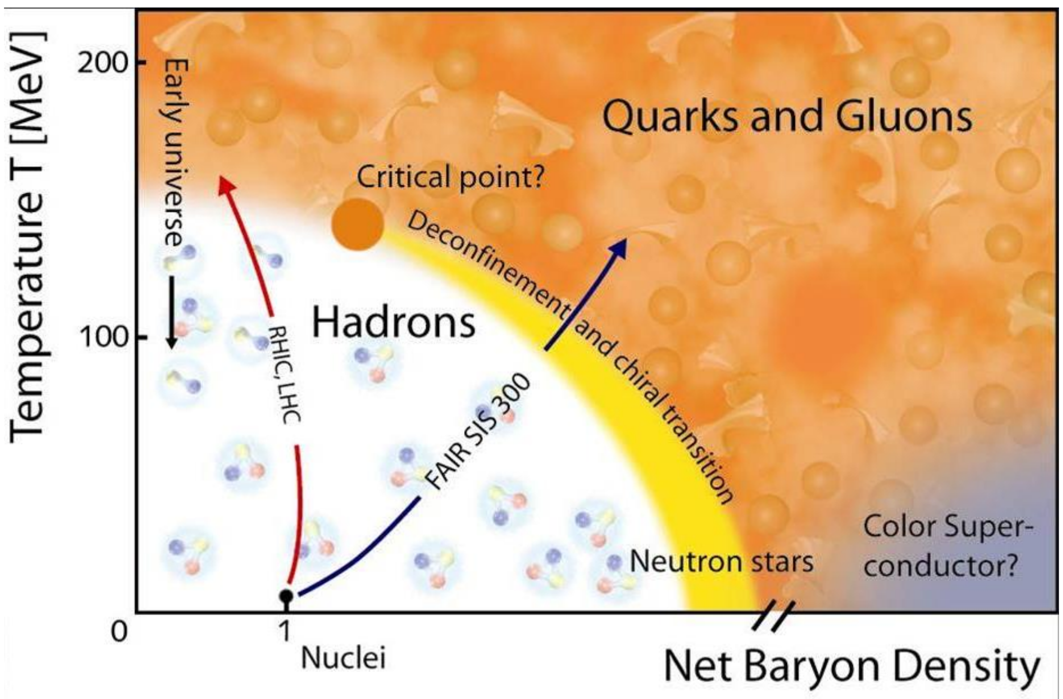
for the ALICE Collaboration

Heavy-Ion Collisions

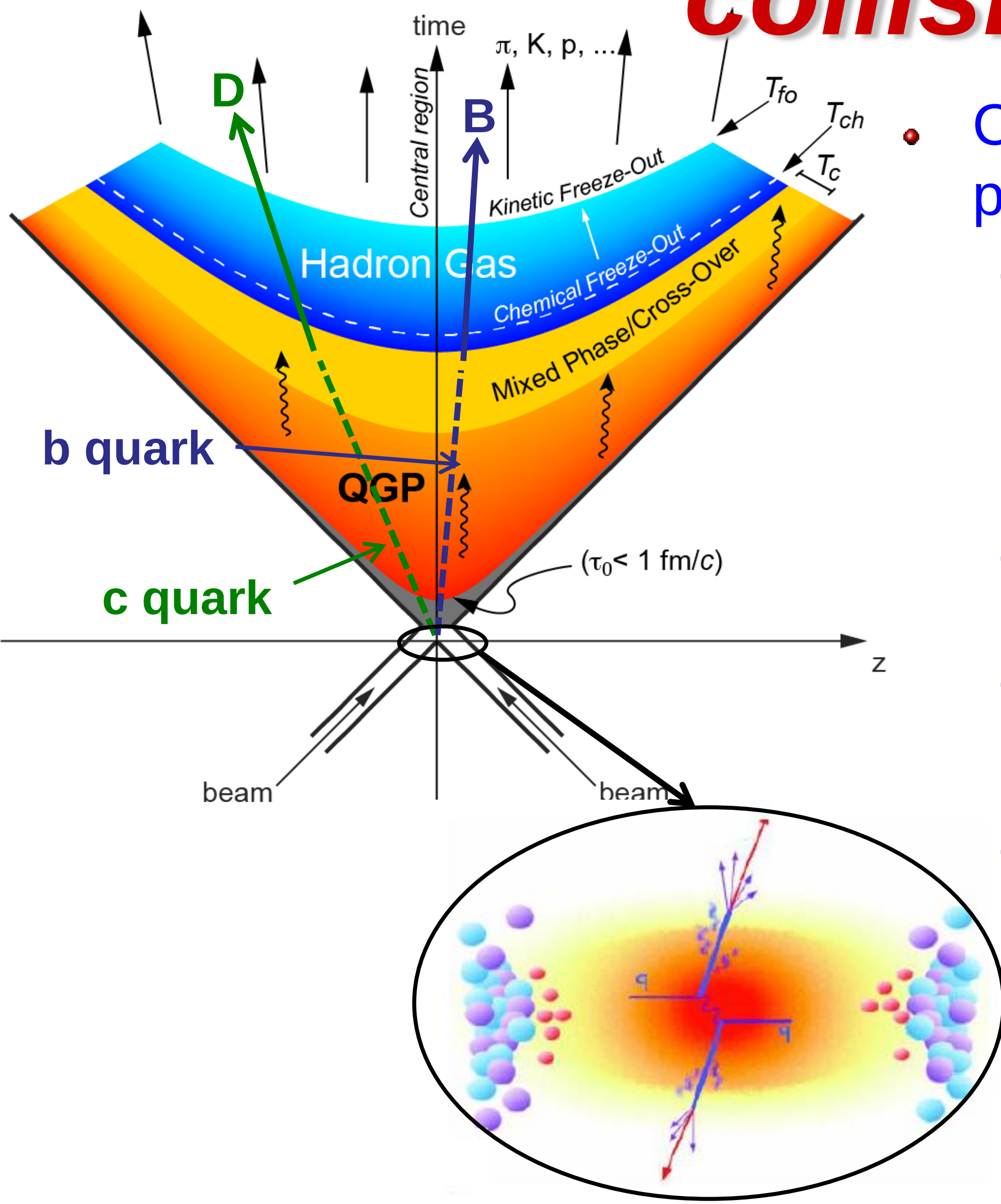
- Goal: study the properties of nuclear matter at extreme conditions of temperature and energy density
  - ➩ Transition to a state where quarks and gluons are deconfined (Quark Gluon Plasma, QGP)
    - ✓ ***From lattice QCD: $T_C \approx$ 145-160 MeV $\rightarrow \varepsilon_C \approx$ 0.5 GeV/fm^3***

📖 **Bazavov et al, PRD90 (2014) 094503**

📖 **Borsanyi et al, JHEP 1009 (2010) 073**



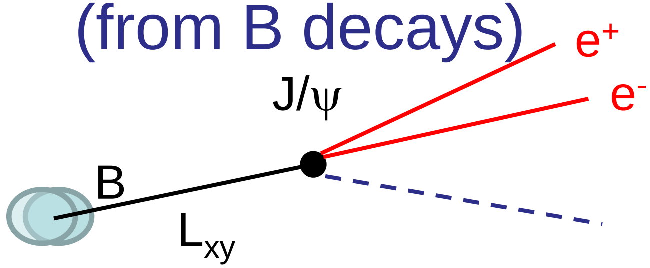
Heavy flavours (HF) in heavy-ion collisions



- Charm and beauty quarks: unique probes of the medium
  - Produced at the very early stage of the collision in partonic scattering processes with large Q^2
    - ✓ ***pQCD can be used to calculate initial cross sections***
  - Small rate of thermal production in the QGP ($m_{c,b}$>>T)
  - Large mass, short formation time
    - ✓ ***Experience the entire evolution of the medium***
  - Interactions with medium constituents don't change the flavor, but can modify the phase-space distribution of heavy quarks

Heavy flavours in ALICE

Non-prompt J/ψ (from B decays)



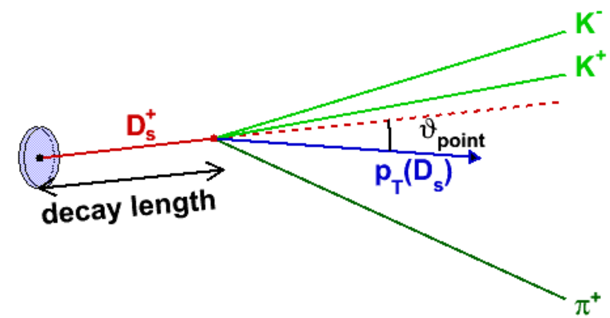
D-meson hadronic decays

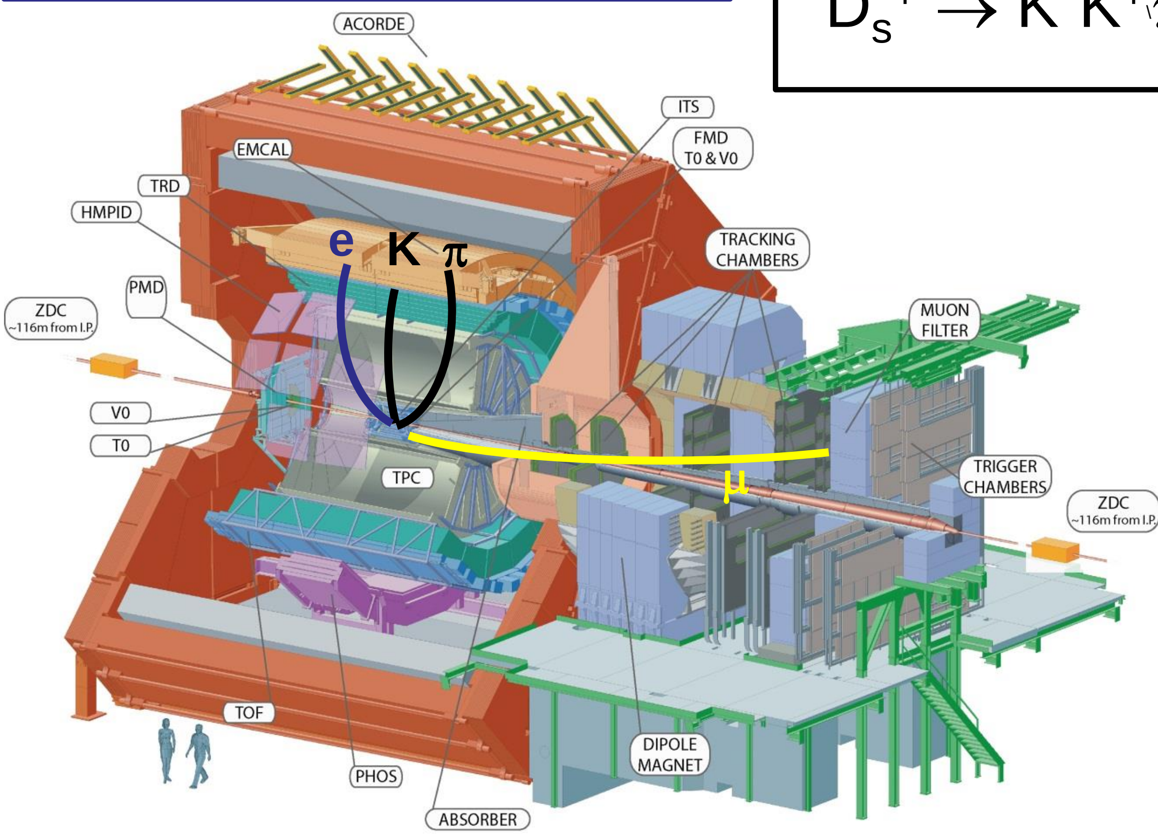
$D^0 \rightarrow K^- \pi^+$

$D^+ \rightarrow K^- \pi^+ \pi^+$

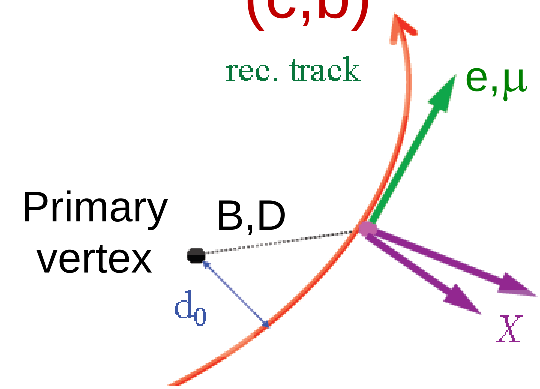
$D^{*+} \rightarrow D^0 \pi^+$

$D_s^+ \rightarrow K^- K^+ \pi^+$



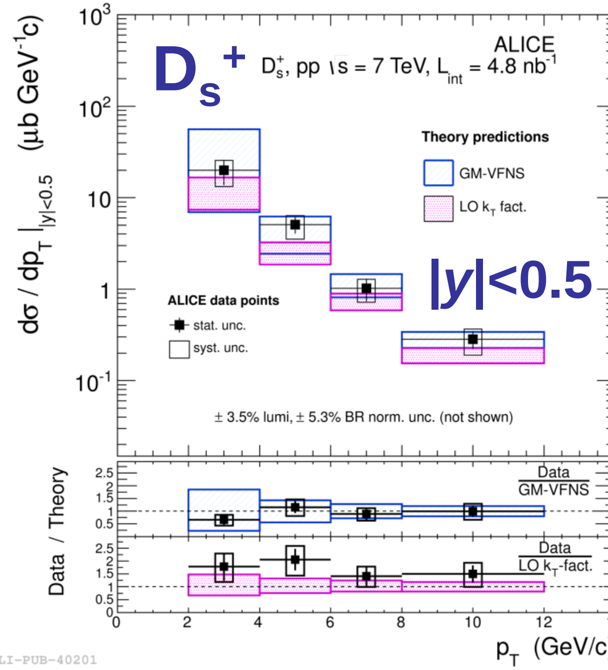


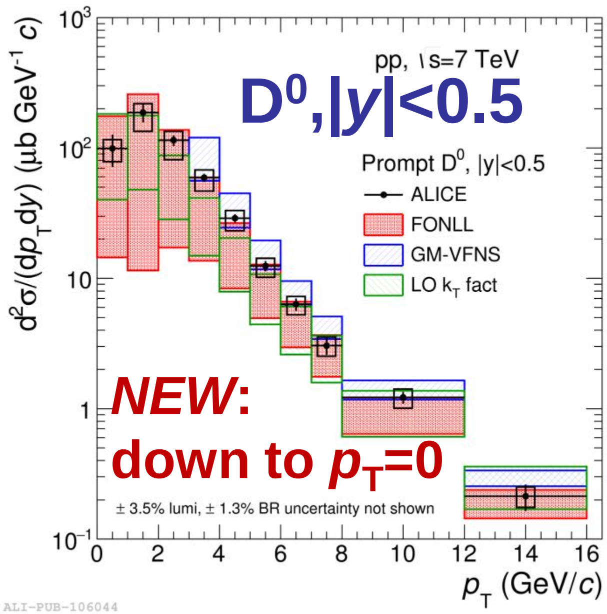
Semi-leptonic decays (c,b)

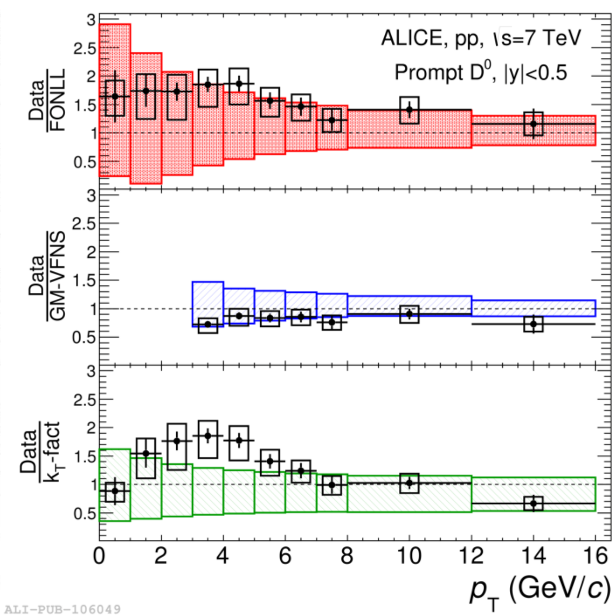


Charm production in pp collisions

- HF production cross sections in pp collisions **described by pQCD** calculations within uncertainties
  - ⇨ FONLL
    - 🕮 Cacciari et al., JHEP 1210 (2012) 137
  - ⇨ GM-VFNS
    - 🕮 Kniehl et al., EPJ C72 (2012) 2082
  - ⇨ LO k_T-factorization
    - 🕮 Maciula, Szczurek, PRD 87 (2013) 094022





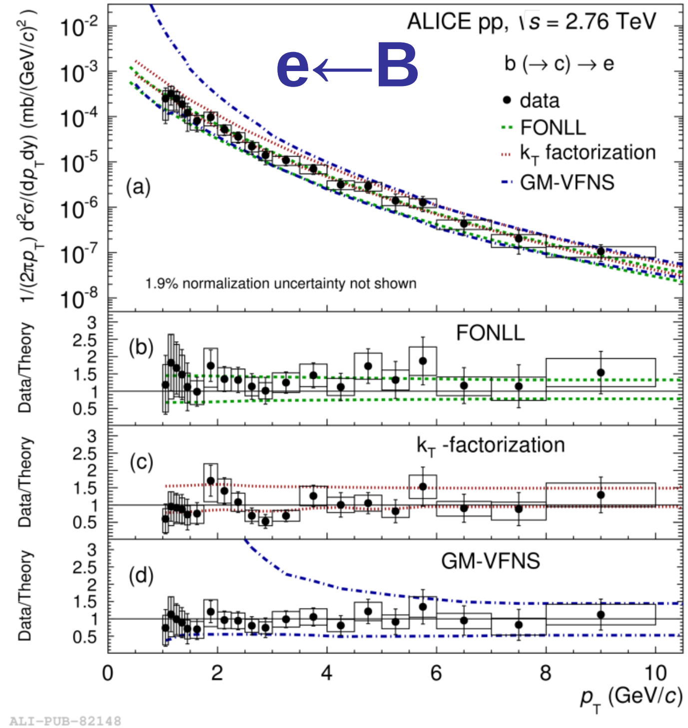


D-meson cross-section on the upper side of the FONLL uncertainty band, as at lower √s

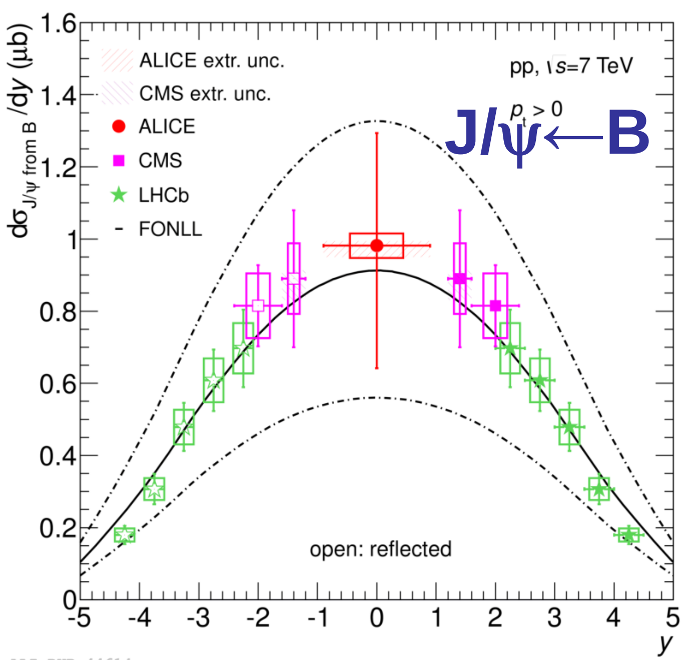
🕮 ALICE, JHEP01 (2012) 128
🕮 ALICE, JHEP07 (2012) 191
🕮 ALICE, PLB718 (2012) 279
🕮 ALICE, arXiv:1605.07569

Beauty production in pp collisions

- HF production cross sections in pp collisions **described by pQCD** calculations within uncertainties
  - **FONLL**
    - 📖 **Cacciari et al., JHEP 1210 (2012) 137**
  - **GM-VFNS**
    - 📖 **Kniehl et al., EPJ C72 (2012) 2082**
  - **LO k_T-factorization**
    - 📖 **Maciula, Szczurek, PRD 87 (2013) 094022**



📖 **ALICE, PRD 86 (2012) 112007**
📖 **ALICE, PLB 738 (2014) 97**

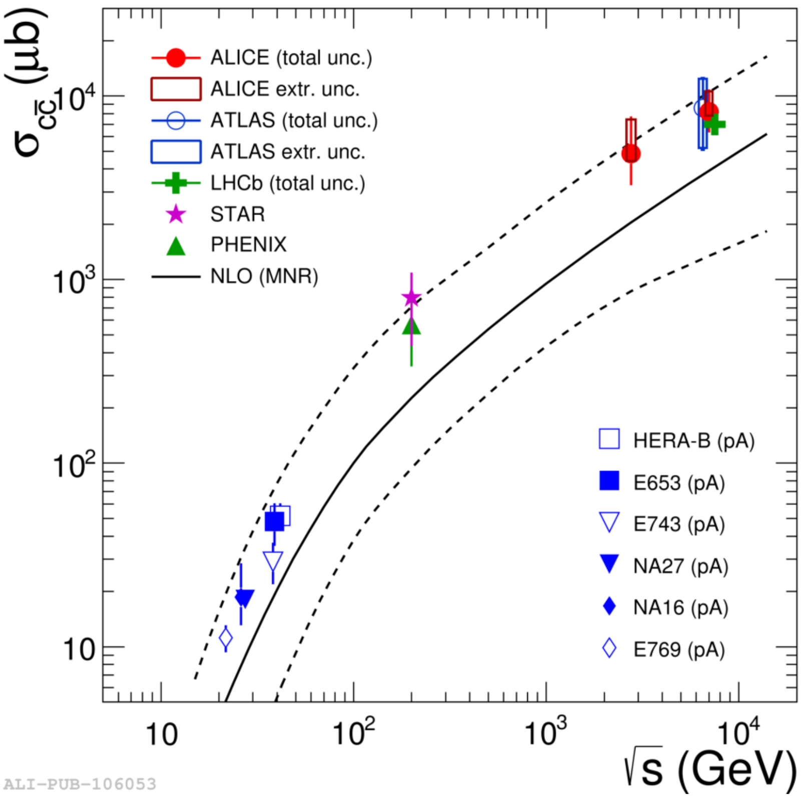


Beauty cross-section well described by FONLL as at lower √s

📖 **ALICE, JHEP 1211 (2012) 065**
📖 **CMS, EPJ C71 (2011) 1575**
📖 **LHCb, EPJ C71 (2011) 1645**

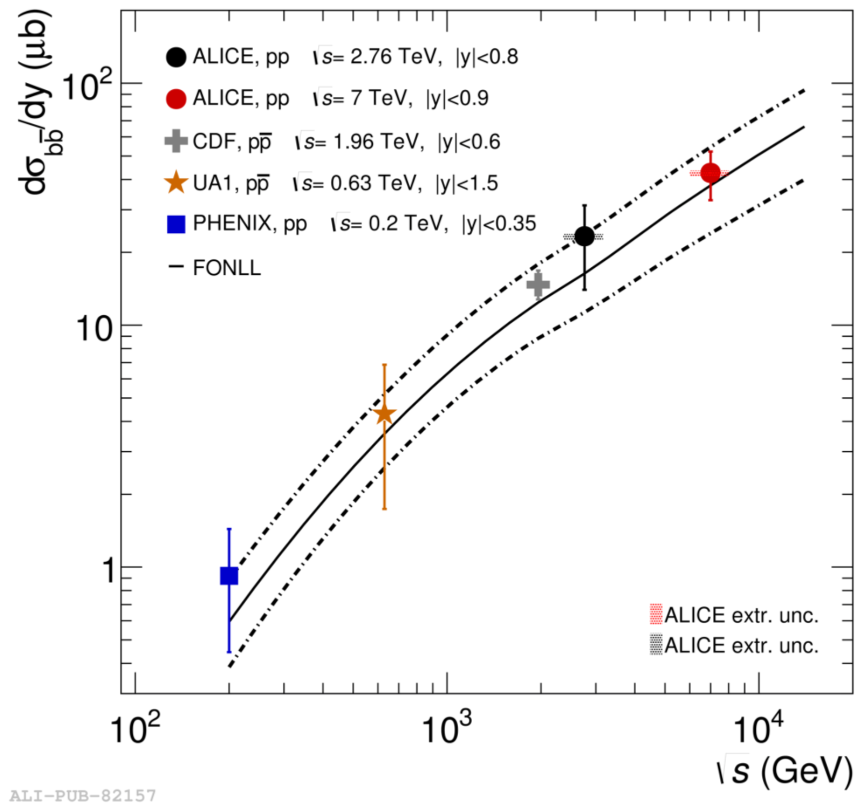
HF production cross section

Charm



📖 **ALICE, arXiv:1605.07569**

Beauty



📖 **ALICE, PLB 738 (2014) 97**

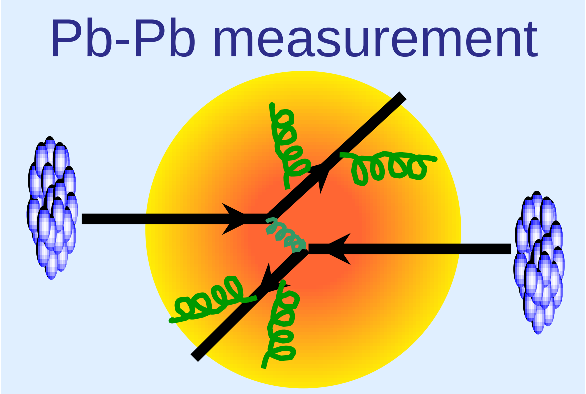
- Total charm and beauty production cross sections described by NLO pQCD calculations within uncertainties
  - ⇨ Charm on the upper edge of the theoretical uncertainty band at all collision energies

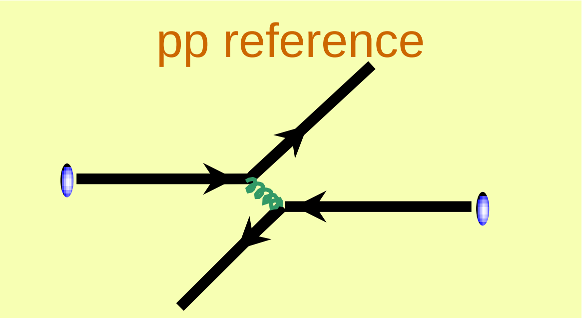
Nuclear modification factor

- Production of HF in nuclear collisions
  - ⇨ Expected to scale with the number of nucleon-nucleon collisions N_{coll} (**binary scaling**)
- Observable: **nuclear modification factor**

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} \sim \frac{QCD\ \text{medium}}{QCD\ \text{vacuum}}$$

- If no nuclear effects are present → R_{AA}=1

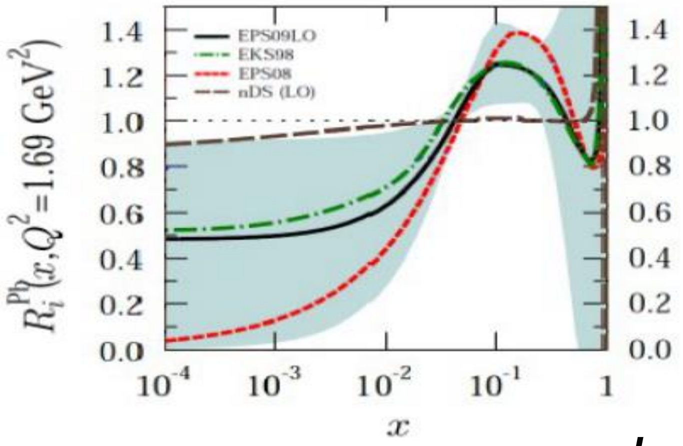


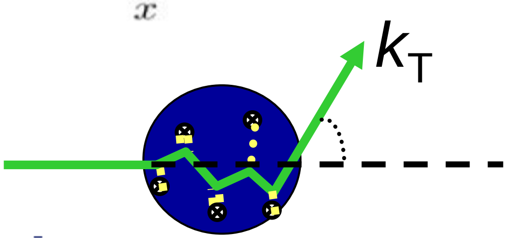


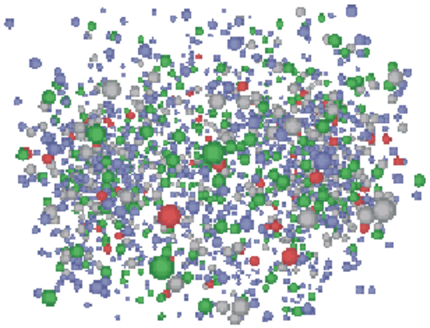
- Interactions with the constituents of the hot, dense and deconfined medium created in the collision can modify (→R_{AA}≠1) the phase space distribution of heavy quarks
  - ⇨ In-medium **parton energy loss**
    - ✓ ***via elastic collisions and gluon radiation***
  - ⇨ Collective flow
  - ⇨ In-medium hadronization

Cold nuclear matter effects: p-Pb collisions

- GOAL: assess the role of **cold nuclear matter** (CNM) **effects**
  - ⇨ **Initial-state** effects:
    - ✓ ***Nuclear modification of the PDFs***
      *→ **shadowing** at low Bjorken-x is the dominant effect at LHC energies*
    - ✓ ***Initial-state energy loss***
    - ✓ ***k_T broadening***
      → due to multiple collisions of the parton before the hard scattering
  - ⇨ **Final-state** effects
    - ✓ ***Final-state energy loss***
    - ✓ ***Interactions with the particles produced in the collision***
      → collective expansion?
      → Mini QGP?
- Crucial for interpretation of Pb-Pb results

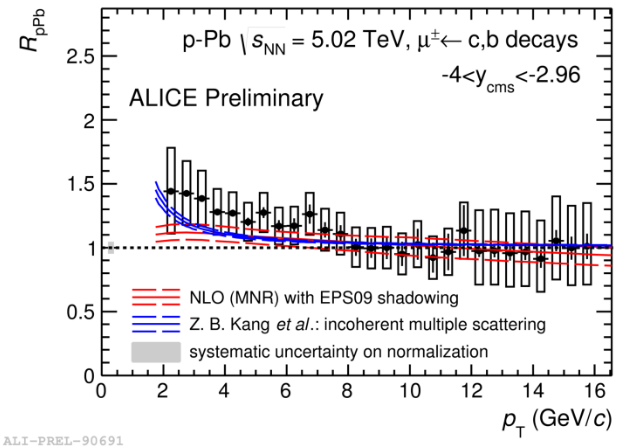




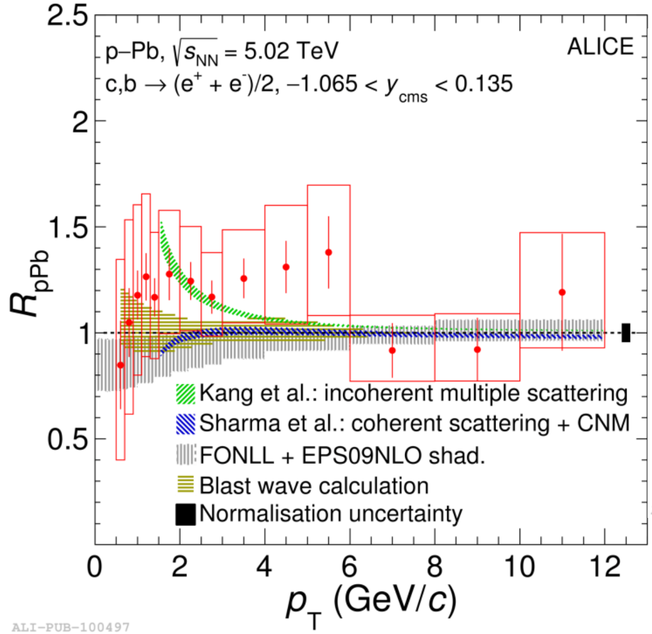


HF decay lepton R_{pPb}

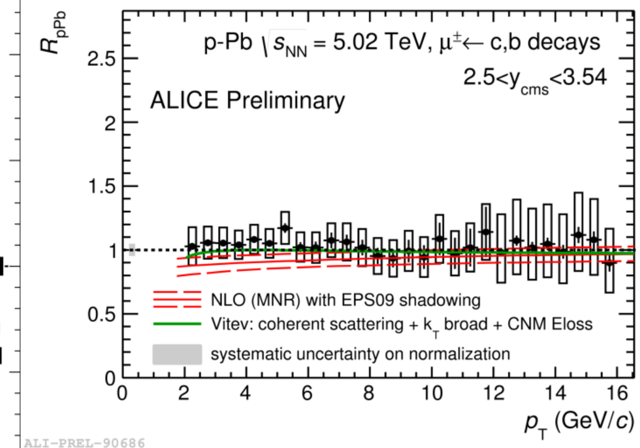
Backward rapidity (Pb-going side)



Mid-rapidity



Forward rapidity (p-going side)

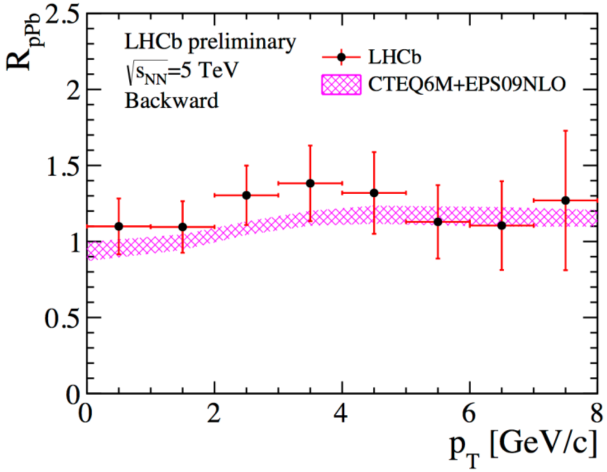


ALICE, PLB754 (2016) 81

- R_{pPb} of HF decay leptons:
  - ⇨ consistent with unity at mid- and forward rapidity
  - ⇨ slightly larger than unity at backward rapidity for 2< p_T< 4 GeV/c
- Described within uncertainties by models including cold nuclear matter effects

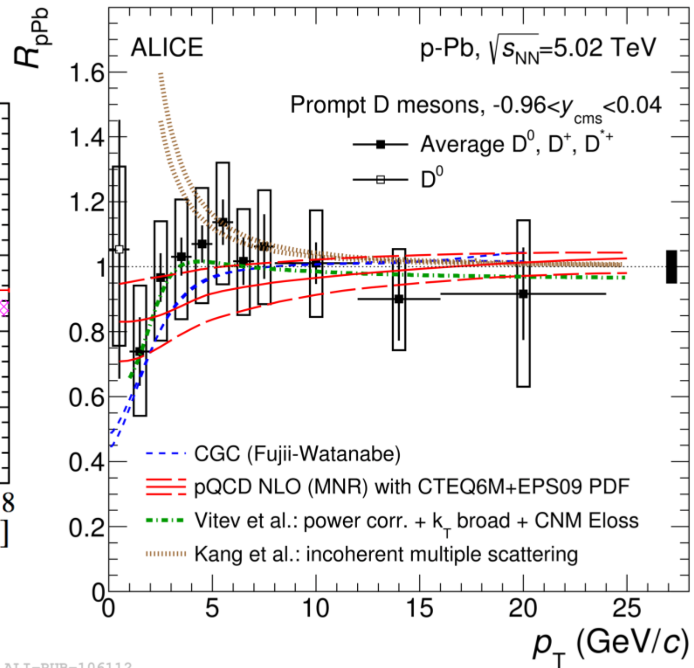
D mesons in p-Pb collisions

Backward rapidity (Pb-going side)



📖 **LHCb-CONF-2016-003**

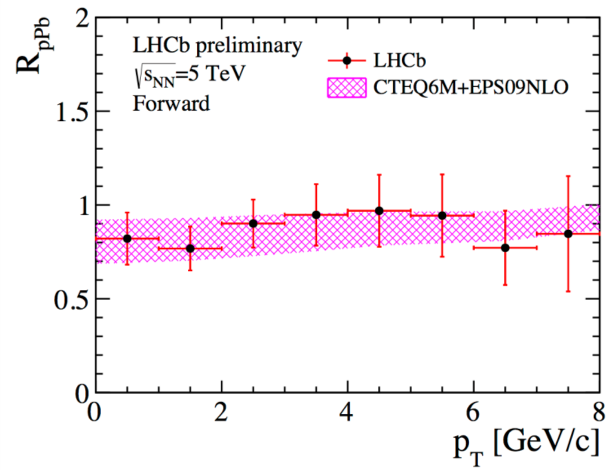
Mid-rapidity



📖 **ALICE, PRL113 (2014), 232301**

📖 **ALICE, arXiv:1605.07569**

Forward rapidity (p-going side)



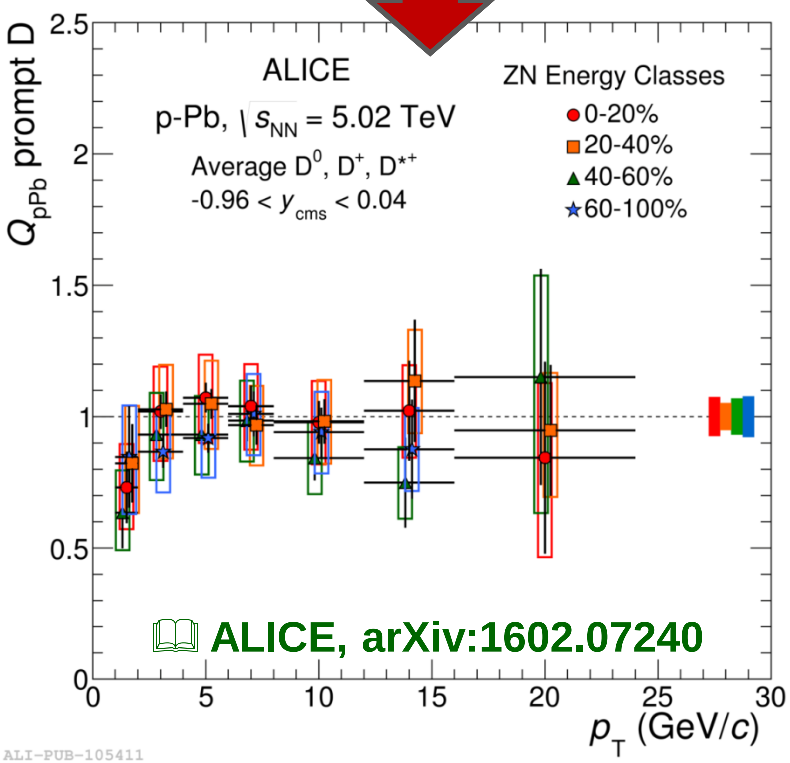
📖 **LHCb-CONF-2016-003**

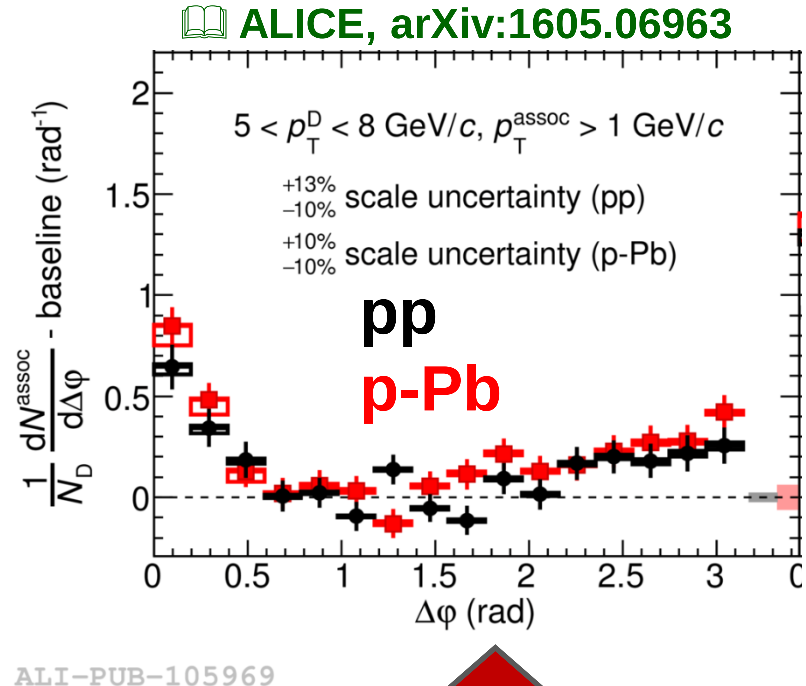
- Charm production in p-Pb collisions described by pQCD calculations including nuclear PDFs and/or other CNM effects

-> No indication of significant cold nuclear matter effects on charm production

More charm in p-Pb collisions

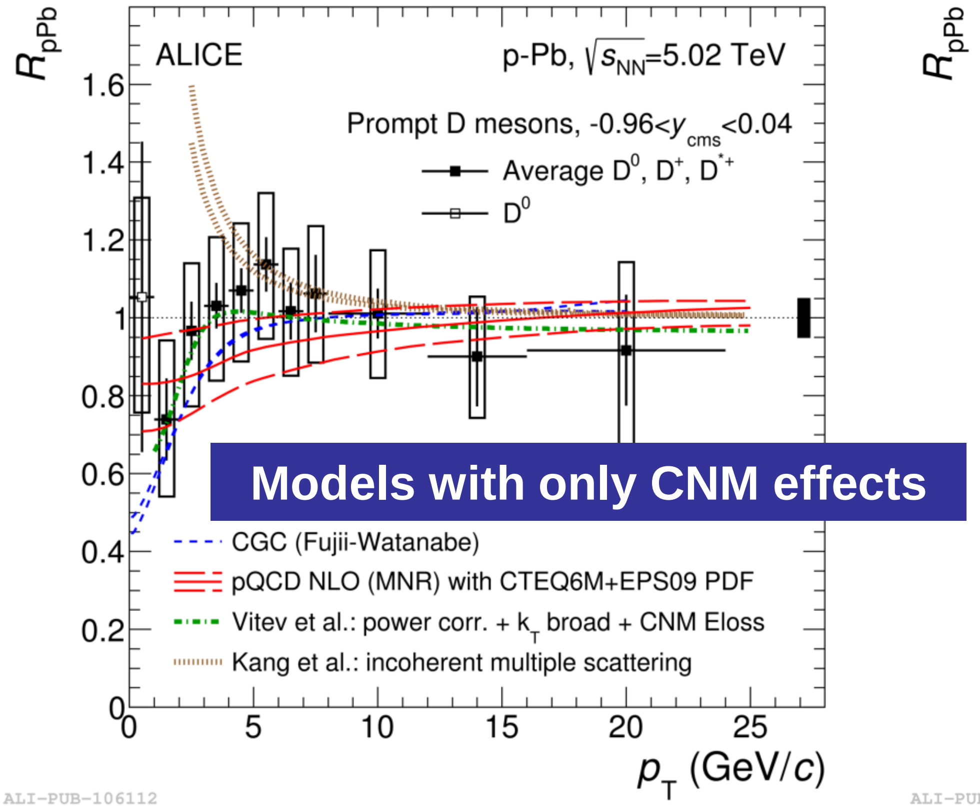
- D-meson nuclear modification factor (Q_{pPb}) in centrality bins
  - Energy deposited in neutron ZDC (ZN) provides an (almost) unbiased estimation of collision centrality
  - Compatible with unity also for the 20% most central p-Pb collisions

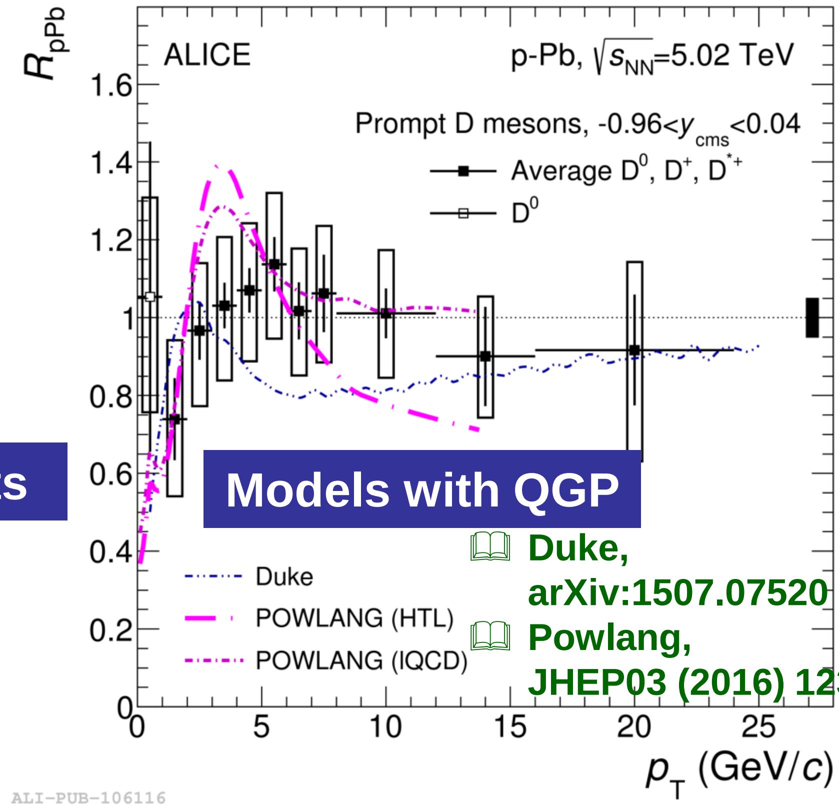




- Azimuthal correlations between D mesons and charged particles
  - Properties of the correlation peak induced by the charm-quark fragmentation are compatible in pp and p-Pb collisions

QGP p-Pb collisions ?





📖 **Duke, arXiv:1507.07520**

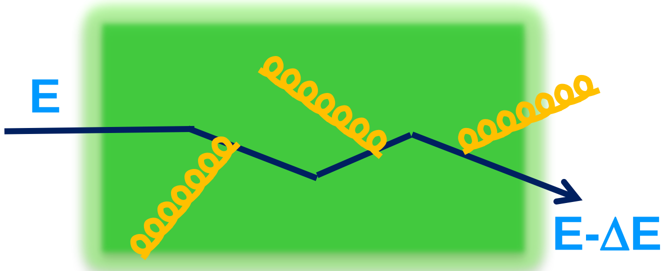
📖 **Powlang, JHEP03 (2016) 123**

- Unexpected results from light-flavour hadrons qualitatively resembling the collective behaviour observed in Pb-Pb collisions
  - ⇨ Also in the charm sector?
- Data on D-meson R_{pPb} compared to Langevin transport models assuming QGP formation in p-Pb collisions
  - ⇨ Current data disfavour a suppression >15% at high p_T
  - ⇨ Can not discriminate the two scenarios with current uncertainties

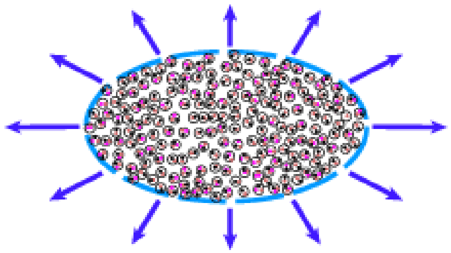
📖 **ALICE, arXiv:1605.07569**

Hot and dense medium effects: Pb-Pb collisions

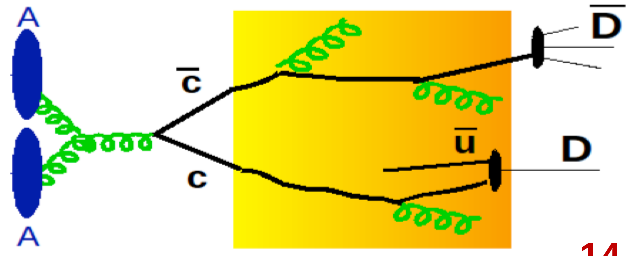
- Interaction of heavy quarks with the QCD medium constituents
  - ⇨ **Energy loss:**
    - ✓ ***Elastic collisions with the medium constituents (-> collisional energy loss)***
    - ✓ ***Gluon radiation***



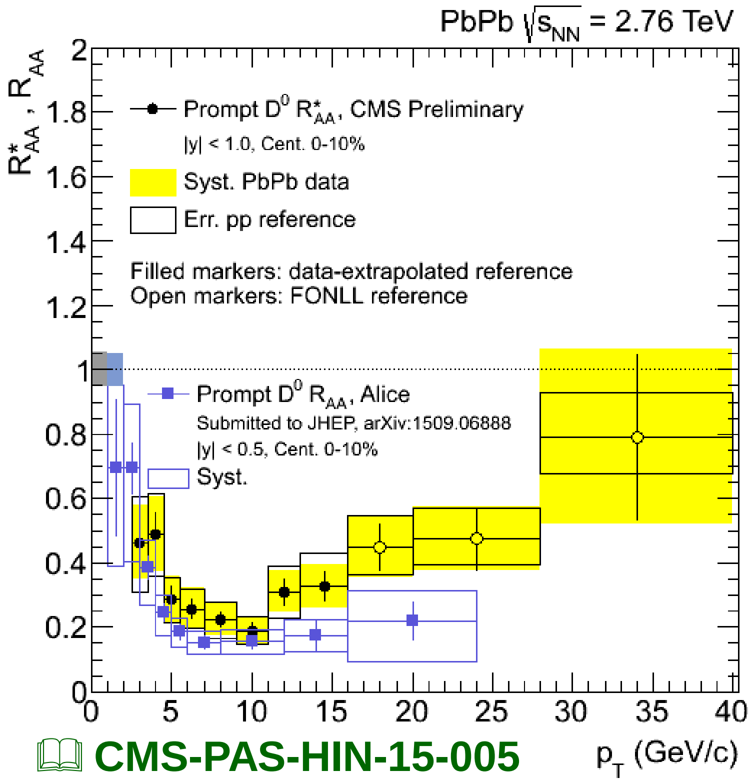
  - ⇨ **Momentum gain due to the "push" from medium collective expansion**
    - ✓ ***Do low-p_T heavy quarks thermalize in the medium?***



  - ⇨ **In-medium hadronization**
    - ✓ ***Hadronization via (re)combination of the charm quark with a (light) quark from the medium ?***



D mesons in Pb-Pb collisions

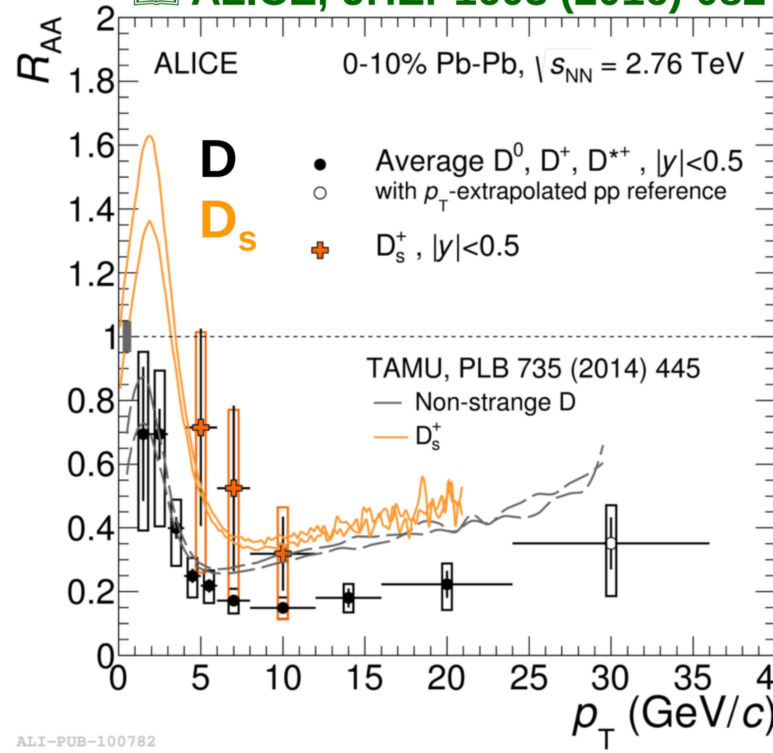


📖 **CMS-PAS-HIN-15-005**

📖 **ALICE, JHEP1603 (2016) 081**

- Strong suppression of prompt D-meson yield in central Pb-Pb collisions
  - ⇨ up to a factor of 5 at p_T≈10 GeV/c

📖 **ALICE, JHEP1603 (2016) 082**



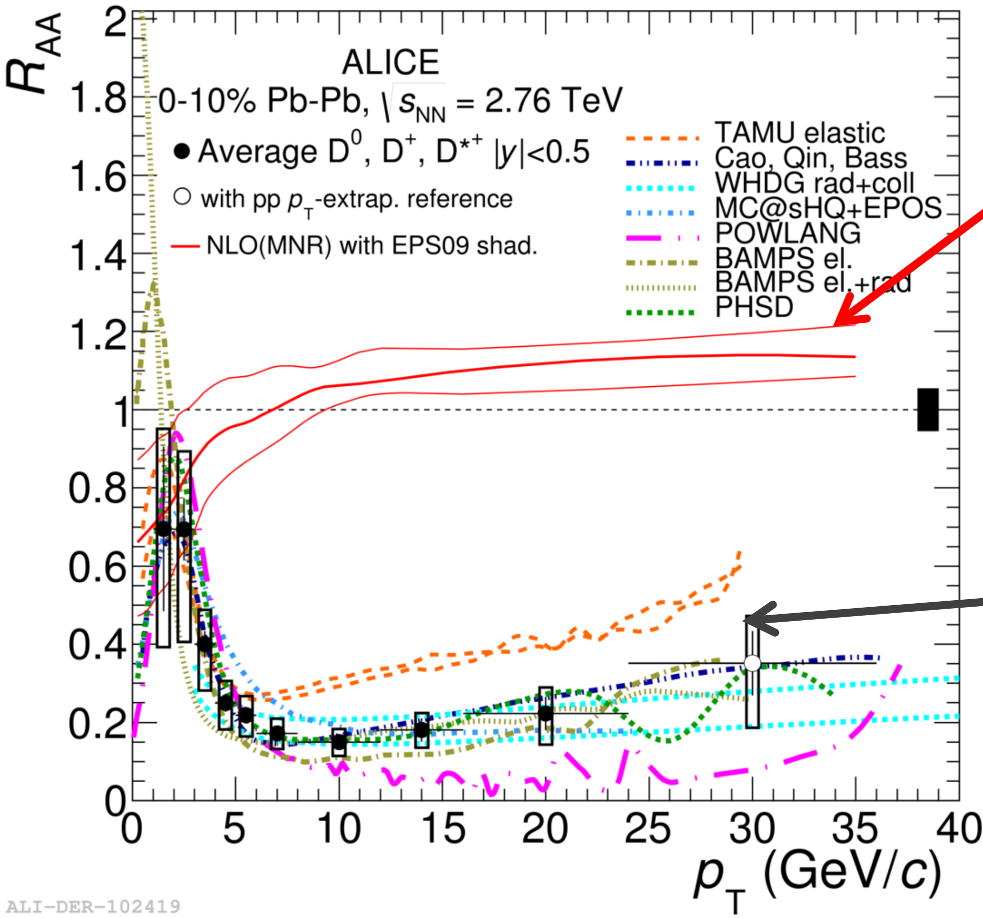
- Hint for less suppression of D_s^+ than non-strange D at low p_T
  - ⇨ Expected if recombination plays a role in charm hadronization

📖 **Kuznetsova, Rafelski, EPJ C 51 (2007) 113**

📖 **He, Fries, Rapp, PLB 735 (2014) 445**

D-meson R_{AA} vs. models

ALICE, JHEP1603 (2016) 081

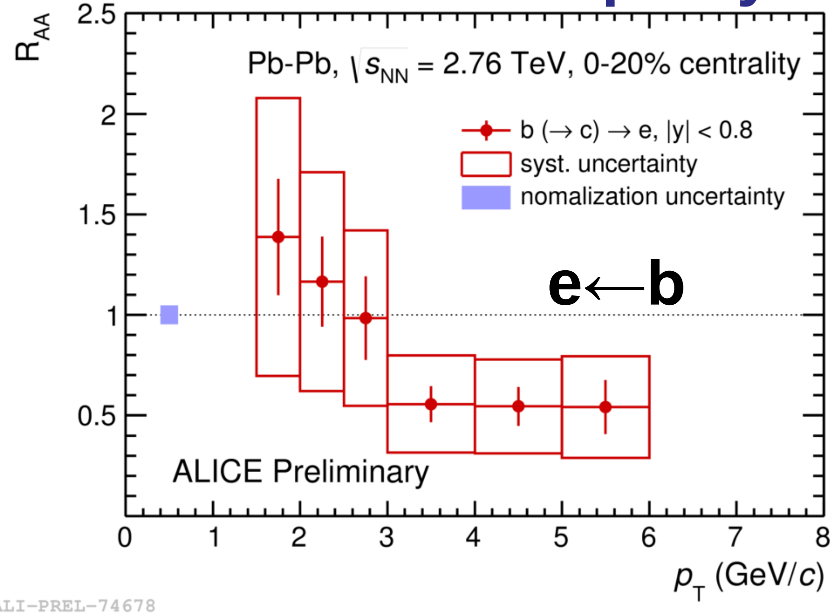


- Expectation from pQCD+nuclear PDFs (no QGP medium)
  - ⇨ Fails in describing the Pb-Pb data
- Models including interactions of charm quarks with medium constituents
  - ⇨ describe qualitatively (and in some cases quantitatively) the data

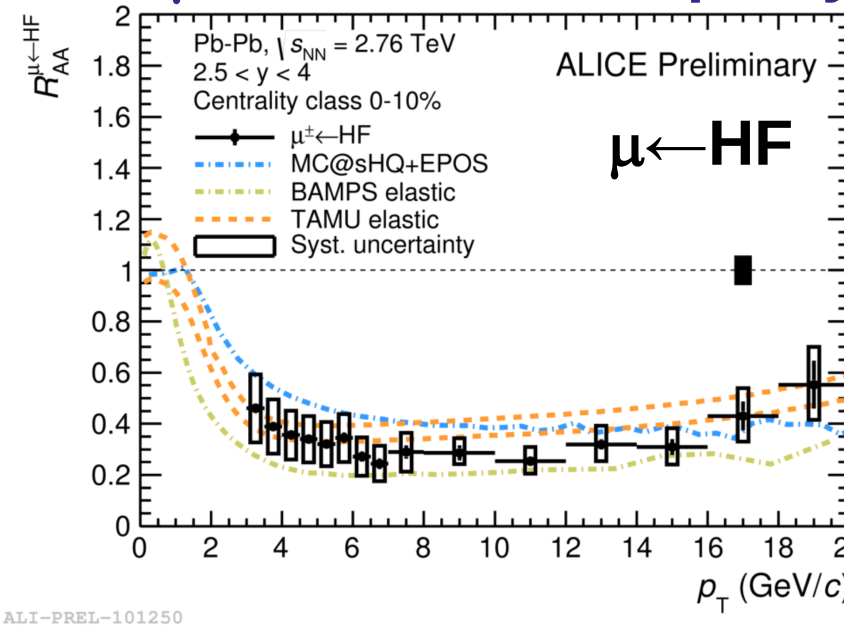
The suppression is a final-state effect
-> due to interactions with the hot and dense medium

HF decay lepton R_{AA}

e←b at mid-rapidity



μ←HF forward rapidity

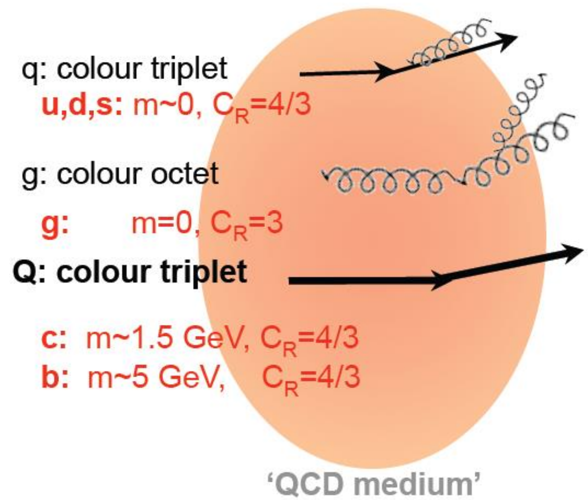


- Indication for beauty decay electron yield suppression in central Pb-Pb collisions for p_T>3 GeV/c
- Production of heavy-flavour decay muons (dominated by beauty for p_T>4-5 GeV/c) suppressed in Pb-Pb collisions
  - ⇨ Suppression described by models including energy loss in QGP

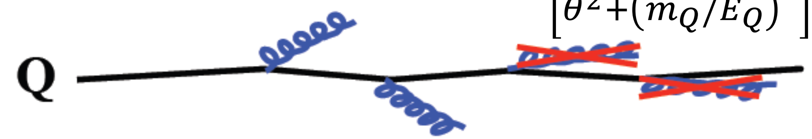
-> substantial energy loss of beauty quarks in the medium

Heavy-quark energy loss

- In-medium energy loss ΔE depends on:
  - ⇨ Properties of the medium (density, temperature, mean free path, …) -> **transport coefficients**
  - ⇨ Path length in the medium (L)
  - ⇨ Properties of the parton (**colour charge, mass**) traversing the medium:
    - ✓ ***Casimir coupling factor***
      - ***-> C_R = 3 for gluons***
      - ***-> C_R = 4/3 for quarks***
    - ✓ ***Mass of the quark***
      - ***-> dead-cone effect***



Gluonstrahlung probability $\propto \frac{1}{\left[\theta^2+(m_Q/E_Q)^2\right]^2}$

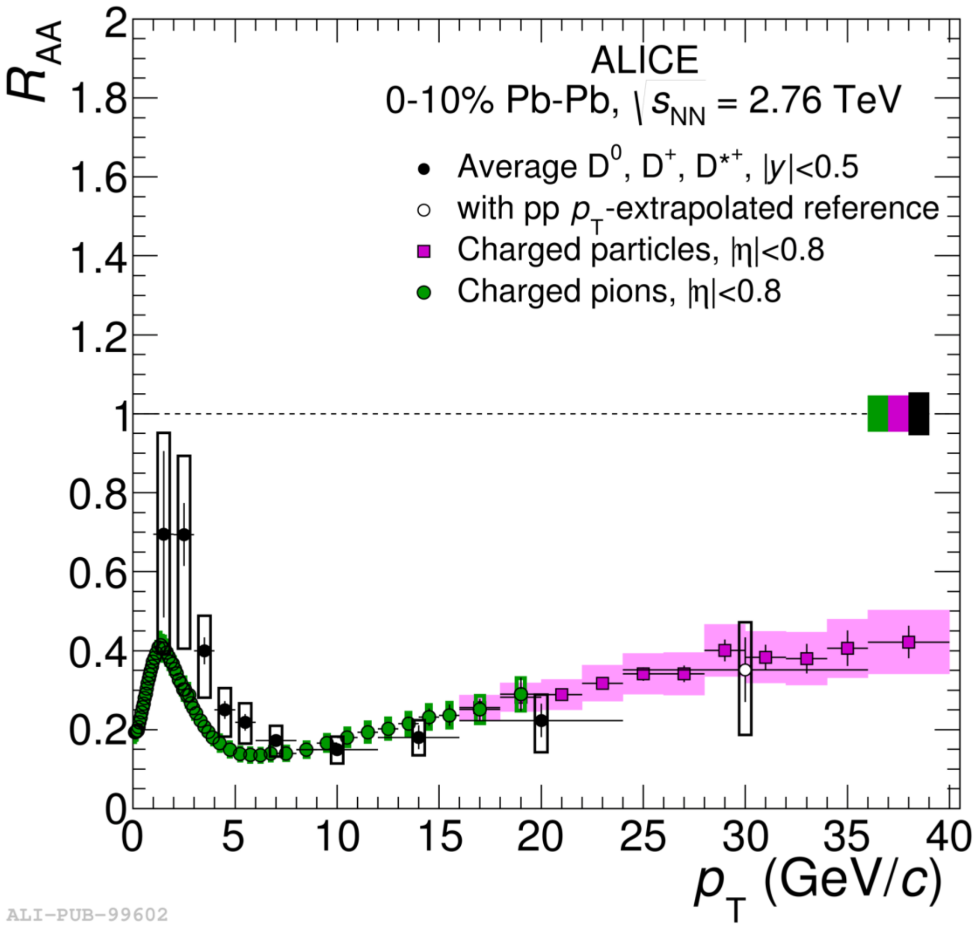


📖 Dokshitzer, Kharzeev, PLB 519 (2001) 199

- Expectation: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Is this reflected in a R_{AA} hierarchy: $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$?

R_{AA}: D mesons vs. pions

- Expectation: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Is this reflected in a R_{AA} hierarchy: $R_{AA}(\pi) < R_{AA}$ (D) $< R_{AA}$(B) ?



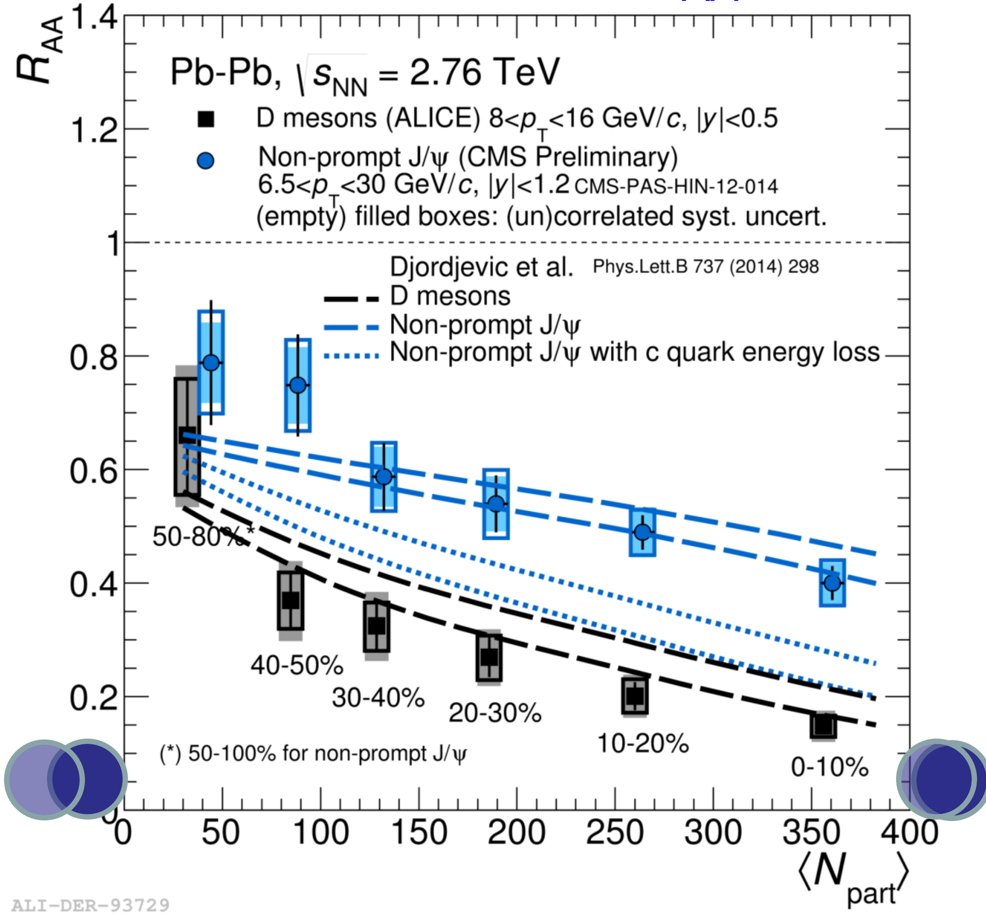
ALI-PUB-99602

📖 **ALICE, JHEP1603 (2016) 081**

- D-meson and pion R_{AA} compatible within uncertainties
- Described by models including
  - energy loss hierarchy ($\Delta E_g > \Delta E_{u,d,s} > \Delta E_c$)
  - different p_T shapes of produced partons
  - different fragmentation functions of gluons, light and charm quarks

R_{AA}: D mesons vs. J/ψ from B

- Expectation: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Is this reflected in a R_{AA} hierarchy: $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$?

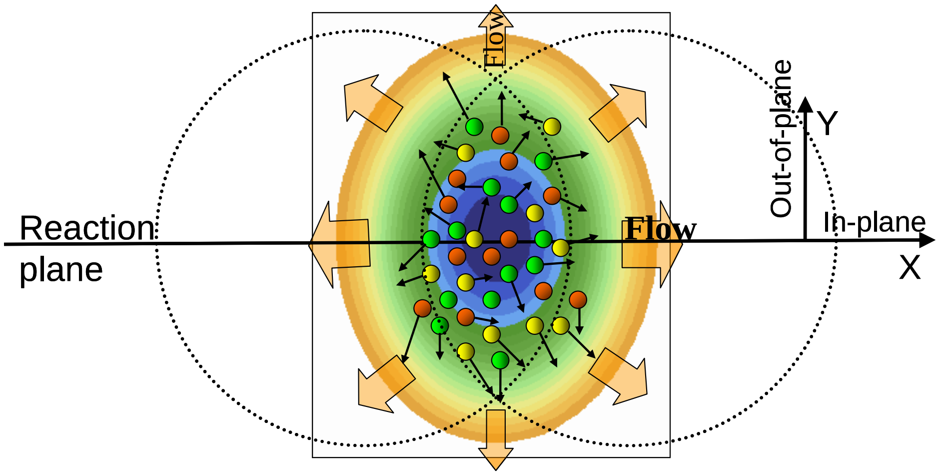


📖 **ALICE, JHEP 1511 (2015) 205**
📖 **CMS-PAS-HIN-12-014**
📖 **CMS-PAS-HIN-15-005**

- Clear indication for $R_{AA}(B) > R_{AA}(D)$
  - ⇨ Consistent with the expectation $\Delta E_c > \Delta E_b$
  - ⇨ Described by models including quark-mass dependent energy loss

-> consistent with prediction of quark-mass dependent energy loss

Azimuthal anisotropy



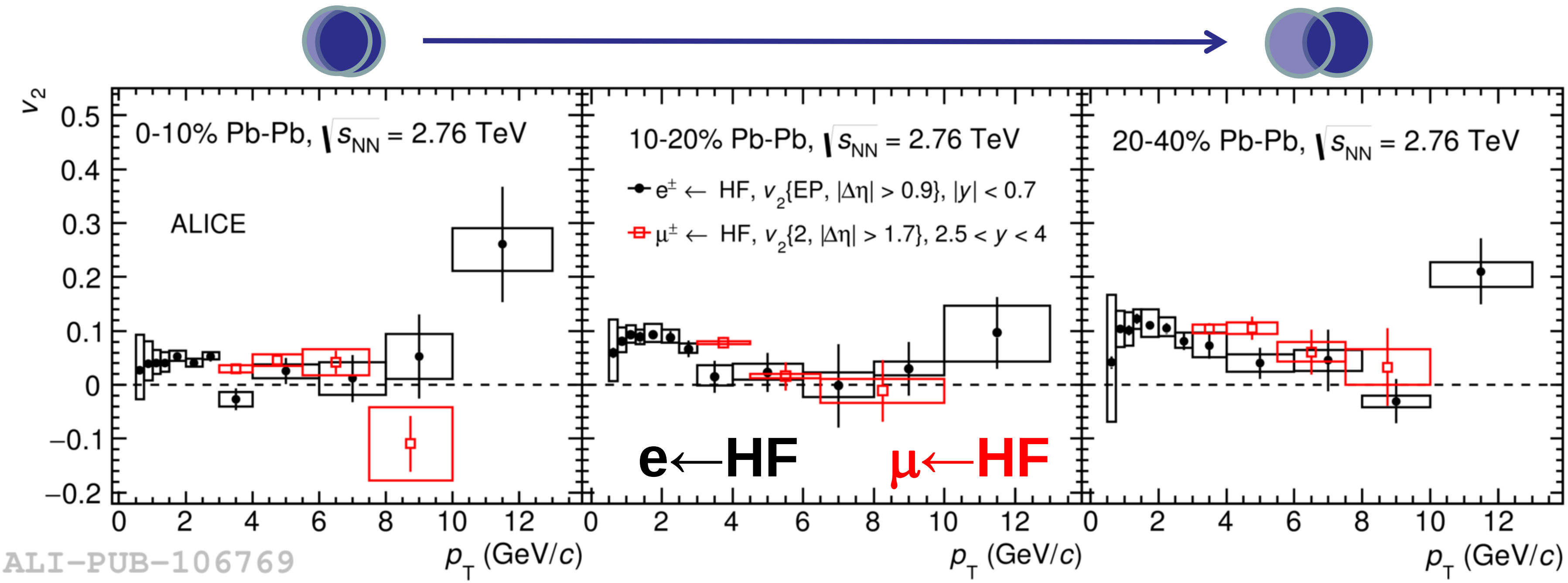
- Initial geometrical anisotropy in non-central heavy-ion collisions
  - ⇨ The impact parameter selects a preferred direction in the transverse plane

- Re-scatterings among produced particles convert the initial geometrical anisotropy into an observable momentum anisotropy
  - ⇨ Collective motion (flow) of the “bulk” (low p_T)
- In addition, path-length dependent energy loss in an almond-shaped medium induces an asymmetry in momentum space
  - ⇨ Longer path length -> larger energy loss for particles exiting out-of-plane
- Observable: Fourier coefficients of the particle azimuthal distribution, in particular 2nd harmonic v_2, called **elliptic flow**

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\{1 + 2v_2\cos[2(\varphi - \Psi_{RP})] + \ldots\}$$

$$v_2 = \langle \cos[2(\varphi - \Psi_{RP})] \rangle$$

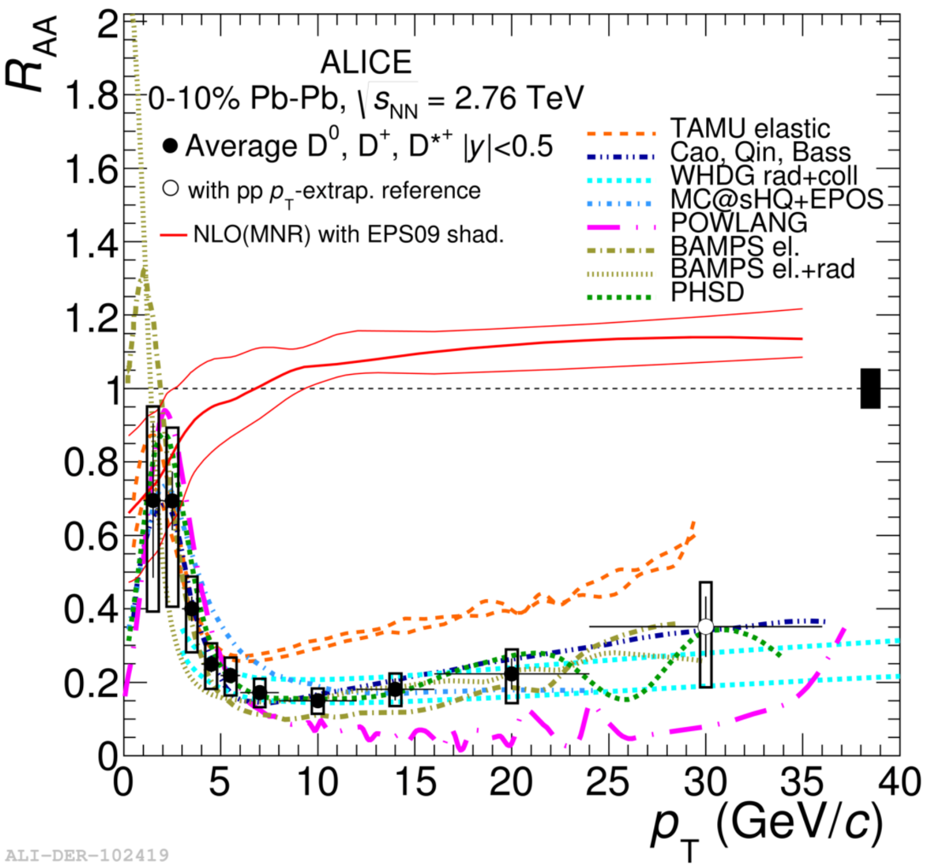
HF decay lepton v_2

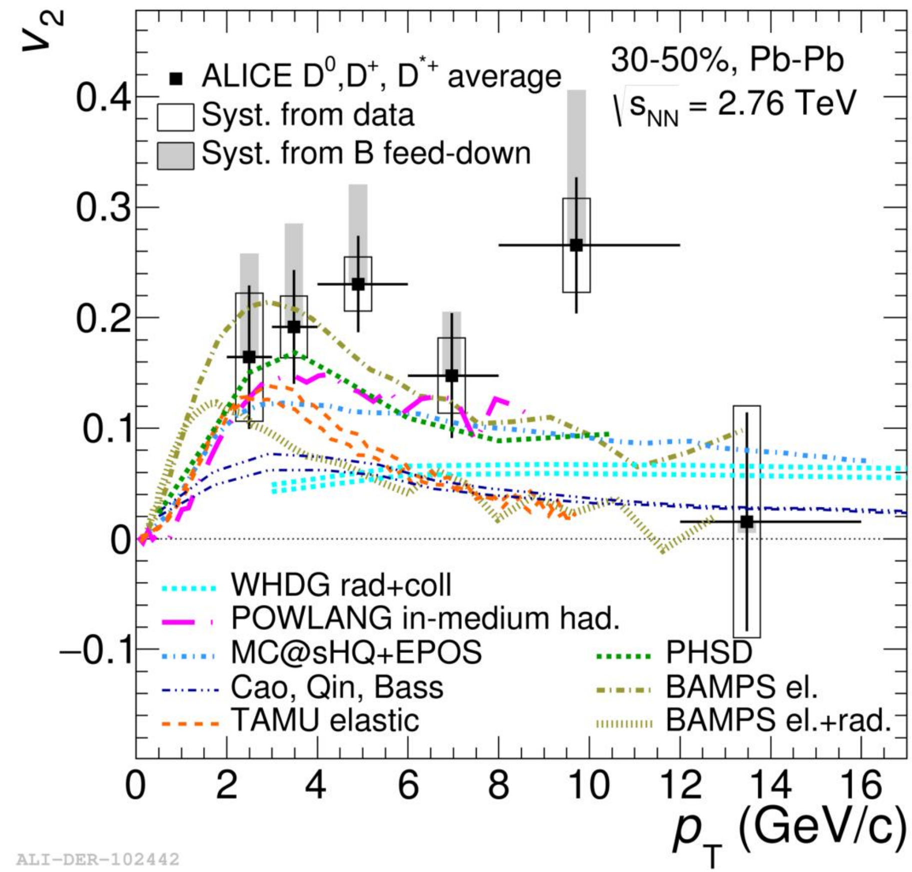


- Positive v_2 of leptons from HF decays at low/intermediate p_T
  - ➩ Similar v_2 at mid and forward rapidity
  - ➩ Elliptic flow increases from central to (semi)peripheral collisions
    - ✓ ***As expected from the evolution of initial geometrical anisotropy with centrality***
- Interactions with the medium constituents transfer to charm quarks information on the azimuthal anisotropy of the system

ALICE, arXiv:1606.00321 **ALICE, PLB753 (2016) 41**

D-meson R_{AA} and v_2 vs. models





- The simultaneous description of D-meson R_{AA} and v_2 is a challenge for theoretical models
  - ⇨ Data have the potential to constrain the models

📖 ALICE, PRL 111 (2013) 102301 📖 ALICE, PRC90 (2014) 034904

Where we are…

- pp collisions
  - ⇨ Production cross section described by pQCD calculations
    - ✓ ***HF are a calibrated probe of the medium created in heavy-ion collisions***
- Pb-Pb collisions
  - ⇨ Substantial **modification of D and B meson p_T spectra**
    - ✓ ***Potential to constrain energy loss mechanisms and medium transport coefficients***
  - ⇨ Indication for $R_{AA}^{beauty} > R_{AA}^{charm}$
    - ✓ ***Consistent with the predicted quark-mass dependent energy loss***
  - ⇨ Positive D-meson **elliptic flow**
    - ✓ ***Suggests that charm quarks take part in the collective expansion of the medium***
  - ⇨ Hint for hadronization via **recombination** from the yield of D_s mesons
- p-Pb collisions
  - ⇨ Original motivation: a control experiment
    - ✓ ***Confirm that D and B meson suppression in Pb-Pb at high p_T is a final-state effect***
    - ✓ ***Small cold nuclear matter effects at mid-rapidity***
  - ⇨ But also unexpected results (in light-flavour sector) qualitatively resembling the collective behaviour observed in Pb-Pb collisions

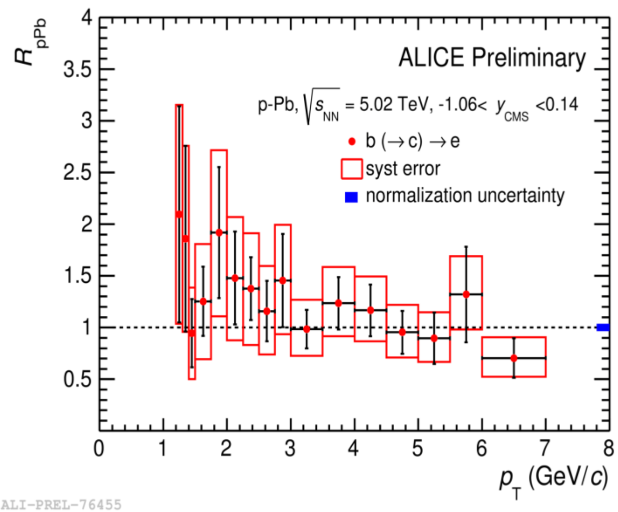
… and what next

- Pb-Pb: larger samples at higher energy
  - ⇨ Improved precision + extended p_T coverage
    - ✓ ***Quantitatively constrain energy loss models***
    - ✓ ***Study whether charm and beauty quarks thermalize in the medium***
  - ⇨ HF hadrochemistry: D_s and baryon-to-meson ratios
    - ✓ ***Constrain the hadronization mechanism (recombination/fragmentation)***
- p-Pb and pp
  - ⇨ Improved precision on pp reference and assessment of CNM effects
    - ✓ ***Crucial role in the interpretation of Pb-Pb results***
  - ⇨ Production vs. multiplicity/centrality
  - ⇨ Collectivity in high multiplicity pp and p-Pb collisions in the HF sector?
- Major step towards high-precision measurements in the HF sector with the detector upgrades after Run2

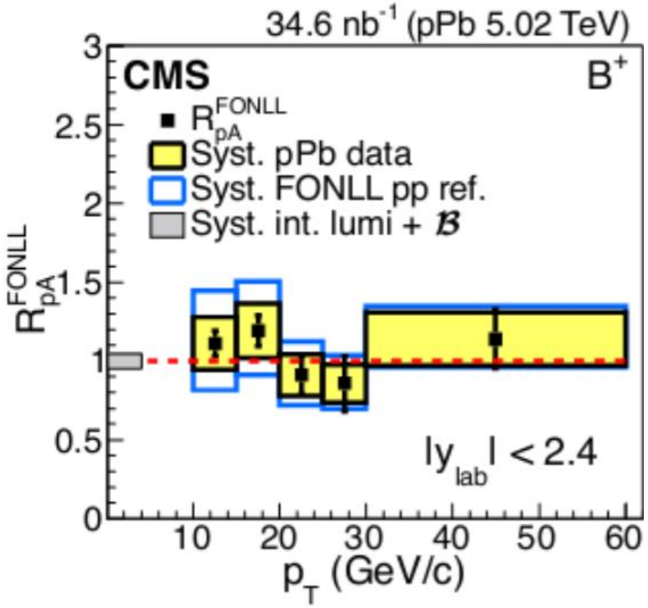
Backup

Beauty in p-Pb collisions

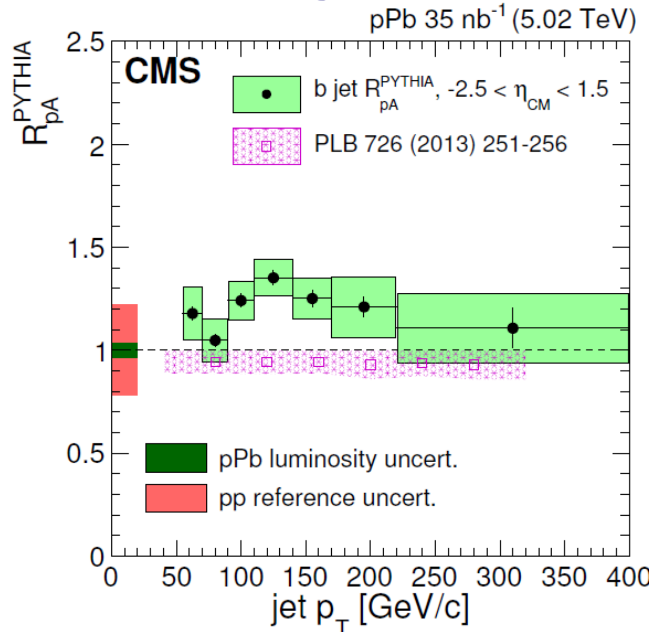
Beauty-decay electrons



B mesons



b-jets

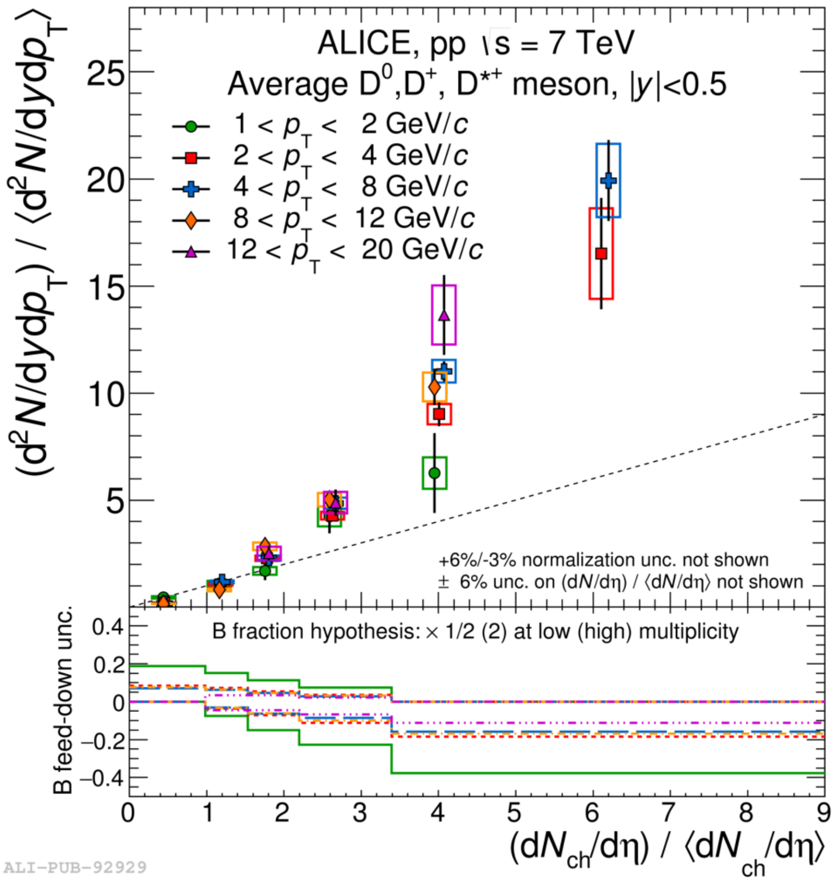


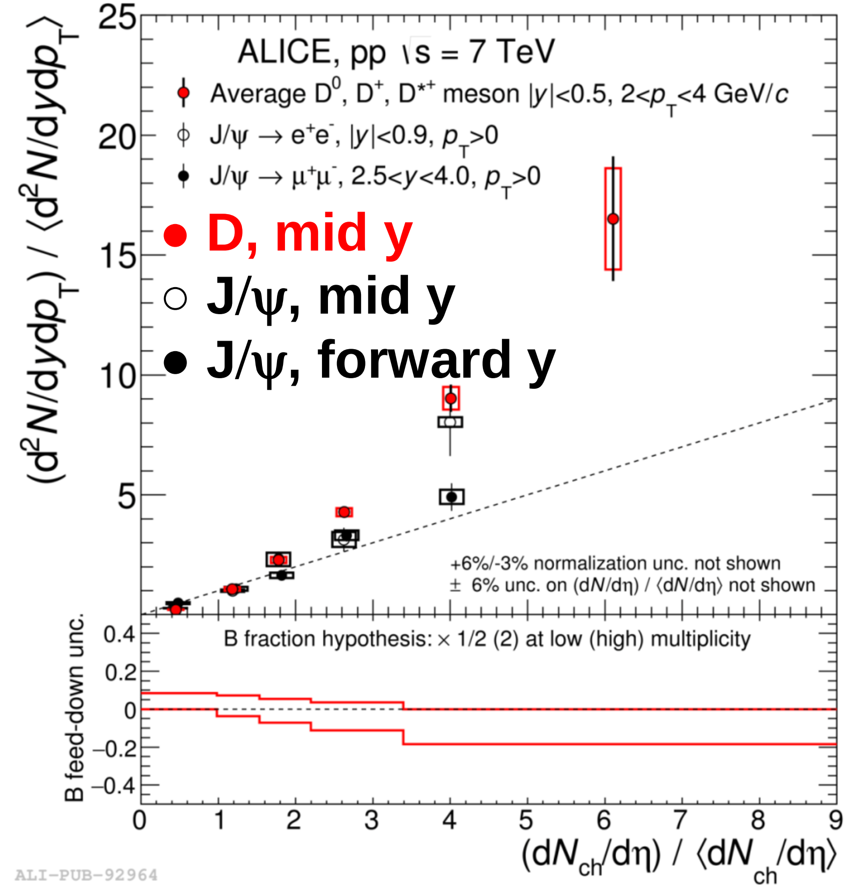
📖 **CMS, PRL 116 (2016) 032301** 📖 **CMS, PLB 754 (2016) 59**

- R_{pPb} of beauty-decay electrons (low p_T), B mesons ($10<p_T<60$ GeV/c) and b-jets (high p_T) consistent with unity

-> No indication of significant cold nuclear matter effects on beauty production

D mesons and J/ψ vs. multiplicity

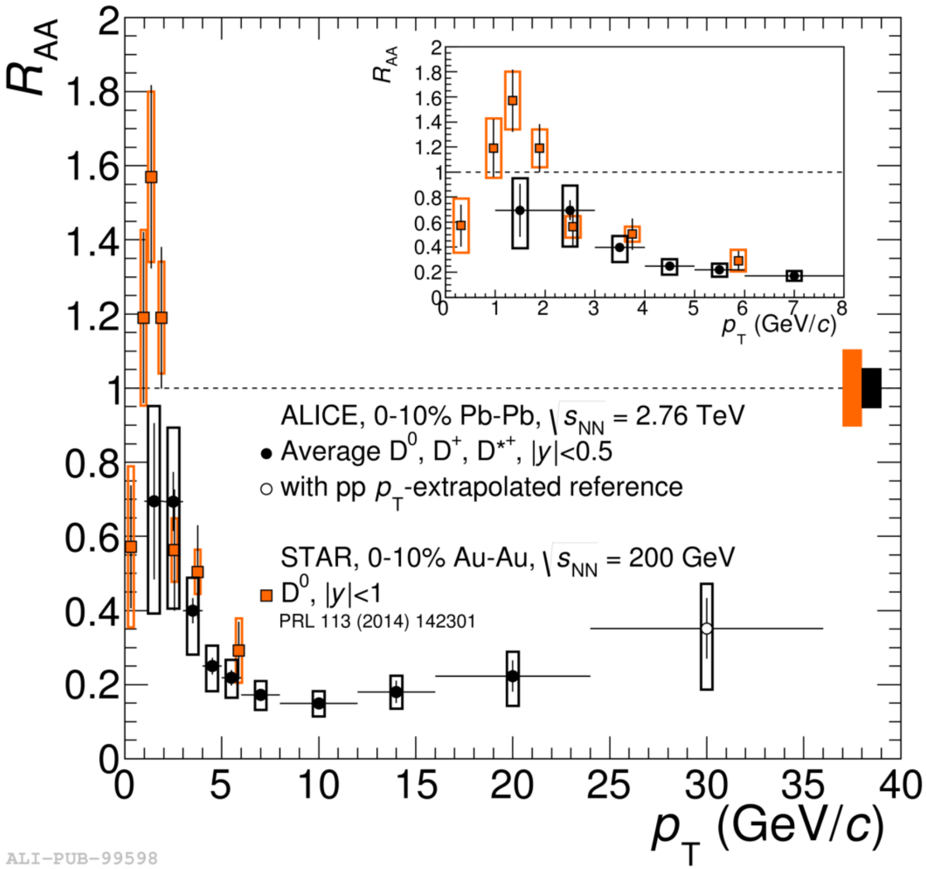




- Per-event yield of D mesons and J/ψ increases with increasing charged-particle multiplicity
  - ⇨ Similar trend in different D meson pT bins
  - ⇨ Described by models including MPIs

ALICE, PLB 712 (2012) 165 **ALICE, JHEP 1509 (2015) 148**

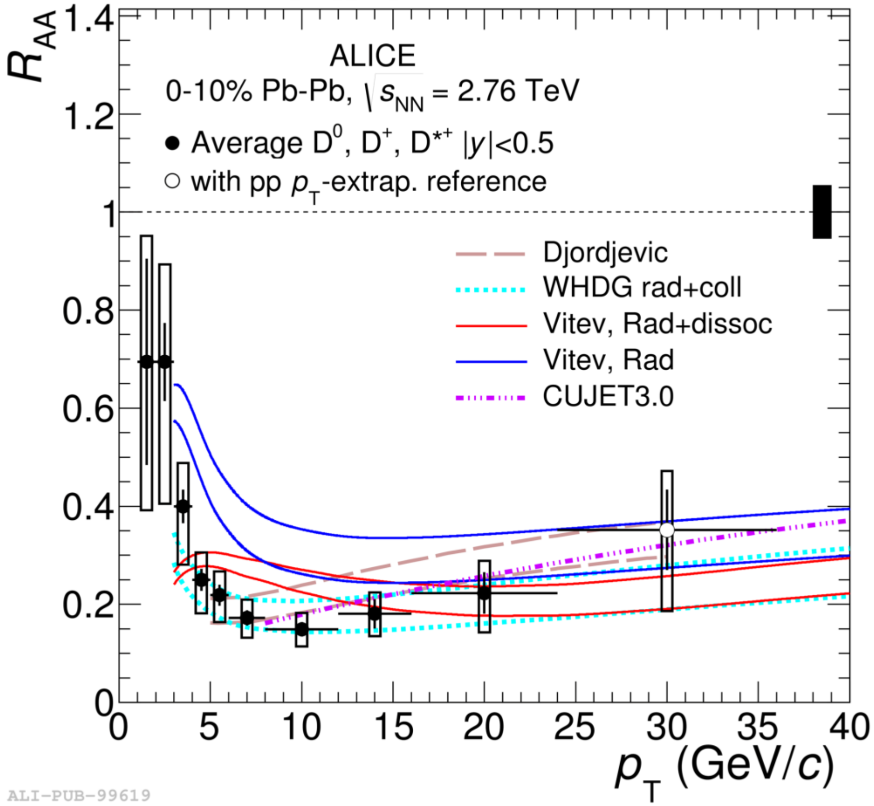
D-meson R_{AA}: LHC vs. RHIC

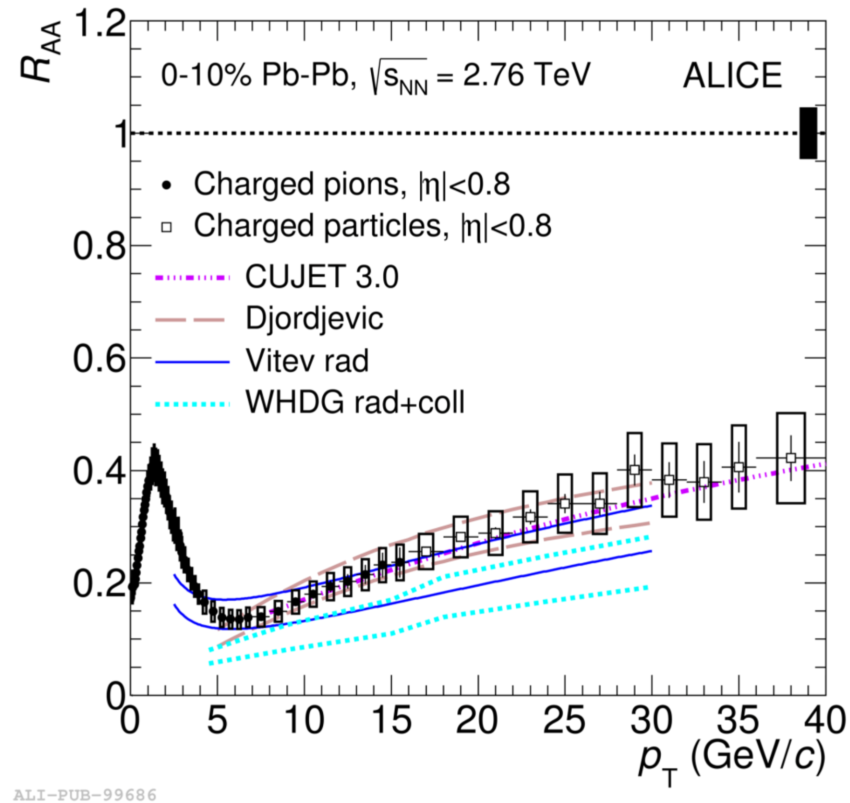


📖 **ALICE, JHEP1603 (2016) 081**
📖 **STAR, PRL 113 (2014) 142301**

- D-meson R_{AA} factor at $\sqrt{s_{NN}}$=0.2 and 2.76 TeV
  - ⇨ Similar R_{AA} for p_T >3 GeV/c
  - ⇨ Maybe different trend at lower p_T
- Many effects are different at different collision energies:
  - ⇨ Different p_T shape of produced charm quarks / pp reference
  - ⇨ Different shadowing
  - ⇨ Different radial flow
  - ⇨ Different medium density and energy loss
- Some theoretical models can describe both measurements reasonably well

R_{AA}: D mesons vs. pions





- D-meson and pion R_{AA} compatible within uncertainties
- Described by models including
  - ⇨ energy loss hierarchy ($\Delta E_g > \Delta E_{u,d,s} > \Delta E_c$)
  - ⇨ different p_T shapes of produced partons
  - ⇨ different fragmentation functions of gluons, light and charm quarks

📖 **ALICE, JHEP1603 (2016) 081**